SECTION V

CONSERVATION ISSUES

OF PROTECTIVE GLAZING

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PRESERVING STAINED GLASS WITH PROTECTIVE GLAZING

Stained glass windows are installed for the purpose of elevating the human spirit and beautifying our manmade environment. They are designed to be appreciated for color, line and texture. Beyond the possible conservation problems that inappropriate protective glazing may cause, it can dramatically detract from the aesthetic of the windows. It is critical to the success of any protective glazing system that aesthetic, structural and conservation issues are all fully addressed.

Protective glazing (PG) is not a substitute for repair, restoration or continued maintenance. In fact, incorrectly installed, it can actually accelerate the deterioration of the leaded glass, supporting frame and surrounding architectural elements. If the installation is not properly designed, it can prevent or inhibit the regular maintenance of the window and the frame. All forms of PG inhibit or prevent entirely the beneficial effects of rainwater periodically washing the exterior surface of the window. Beyond the positive aesthetic result of cleaner windows, rainwater removes the surface layers of dust and dirt that may adhere to the surface of the glass and often becomes hygroscopic. This moist layer of dirt can create a micro-environment that can be quite detrimental to the glass, lead and framing materials of the window.

PG is too often prescribed for the wrong reasons. Many stewards of stained glass in this country hear of the myriad problems air pollution and acid rain may cause the medieval windows of Europe. An important distinction must be drawn between these ancient windows and our relatively modern stained glass. The glass found in stained glass windows has three basic components: silica, alkali and metallic oxides. In medieval glass, the alkali was provided by adding potash to the glass mix, resulting in a glass high in potassium oxide. This glass is very susceptible to corrosion through attack by air born pollutants and moisture. To conserve this glass, it is important to separate it from the exterior environment. Modern glass, fabricated after the early to mid-19th century, derives its alkali from a soda lime mixture. This results in a glass high in sodium oxide, a much more durable material. There is no need to protect this glass from air born pollutants.

Most stained glass windows in the United States do not need to be protected from the elements. The rare exceptions are the following: windows with very large panel sizes and an insufficient support bar system, thereby susceptible to damage from wind-loading; glass with fragile or unstable fired paint; glass with cold (unfired) paint or unstable glass; and plated windows with irregular, exterior plating levels that may encourage the infiltration of water between the plates.

It is crucial to identify the real cause of damage to the windows in question before determining how to protect them. Is the damage manmade or natural deterioration? Is the source a permanent condition or one that is temporary and can be rectified? The first step should always be to remove the cause of the damage rather than to treat the symptoms of the disease. However, in this unfortunate age of wanton destruction, it is sometimes necessary to take extraordinary precautions to protect our treasured artworks from misguided people. In this capacity, protective glazing serves an important role. Correctly installed, this PG can maximize the protection of the stained glass while having a minimal impact on the window's aesthetic.

CONSERVATION WITH PROTECTIVE GLAZING IN EUROPE

It should be noted that in most European countries, the government is a partner in varying degrees to the conservation of historic buildings and stained glass. Various governments provide funding, some significant, for research, actual conservation and restoration of stained glass. For his dissertation research, Oidtmann conducted in-situ tests in the following medieval churches:

Altenberg, Dom (Cathedral)
Breinig, St. Barbara
Keyenberg, Heilig Kreuz
Koln, Dom (Cathedral)
Lamersdorf, St. Cornelius
Marburg, Elisabethkirche
Monchengladbach, Munsterkirche
Monchengladbach-Hardt, St. Nikolaus
Monchengladbach-Hermges, St. Josef
Rheydt-Giesenkirchen, St. Gereon

He concludes that venting to the inside is best. He makes no distinctions in the quality of protective glazing material.

In the early 1950s the Franz Mayer'sche Hofkunstanstalt, as part of the overall restoration of the war damaged Cathedral in Munich, reinstalled the medieval windows with isothermal glazing under the supervision of Dr. Heinz Merten, the noted German glass expert of the time. During the restoration, a crated pair of windows from the Cathedral were found in the basement of a tower. These windows had been removed from the church in 1830, during an earlier restoration, and replaced by then modern windows. Important for preservation and deterioration research, was the nearly mint condition of these windows. They proved a 110 year old control group, when compared to the weathered and deteriorated condition of the in situ windows. In 1980 the isothermal glazed windows were again studied and found not to have suffered any more in the past. Other medieval windows in Munich that had not been protectively glazed suffered markedly in those 25-30 years of Germany's economic miracle.

Around 1960, notice was made of *new* general deterioration of medieval stained and painted glass. Conservation personnel were consulted and the Corpus Vitrearum formed their special study committee; the general consensus was that the corrosiveness of *air pollution* was the culprit. From this situation, Roy G. Newton has written numerous articles and a book citing scientific evidence relative to air pollution damage on glass, how moisture interacts with glass to form corrosion, weathering of medieval glass, and deterioration and conservation of painted glass. His were the first scientific responses to the deterioration of medieval stained glass. In 1980 Newton gave a lecture at a conservation seminar in which he discussed the results of interspace temperature monitoring at Canterbury Cathedral, on both externally and internally vented stained glass windows. He discussed why Relative Humidity figures could be misleading and why the Dew Point figures were more useful as an indication of the wetness of the air.

ISOTHERMAL GLAZING

As reported in the February 1975 CV Newsletter #13, the British Building Research Establishment and the British Department of the Environment concluded, as a result of an experiment on a simulated cathedral, "isothermal" glazing (the temperature on both sides of the stained glass is the same) is much more efficient than had been previously thought because air velocities in the interspace have sometimes exceeded 1 meter per second, corresponding to 600 changes of air per hour in the cavity." Additional unspent money from the contract was to be used for a similar experiment at York Minister, using a window on the south choir aisle which already had external protective glazing in position. Some adjustable external ventilation of the interspace was going to be introduced so that several conditions could be studied - thermal, air-flow and humidity conditions. Five kinds of sensors were to be used. At the time, an Air Flow Tester Kit manufactured in Germany was obtained from Draeger Safety Limited, with the German makers being DRAGERWERK AG, Lubeck, Germany. In one case at York Minster where the ventilation gap was only 2mm wide, a stream of smoke was introduced at the bottom of the window, travelled up for about 1 meter and then went down again to come out at the bottom, but at a different point. This exercise revealed that air flows are difficult to predict.

The CV NEWSLETTER 41/42, 1988 has an article discussing that beneficial effects of isothermal glazing have "proved to be the most important method for the protection and conservation of stained glass", due to the following reasons:

1. Protection against 'mechanical' damage (stones, storms, hail, wind, sonic boom).
2. Protection against weather (rain, snow, dew, damage of air pollution).
3. Stained glass is no longer the barrier between inside and outside climate.
4. Prevention of condensed water on the painted inner side of glass painting.

However, it is pointed out that the protection of double glazing can only be effective when its installations has certain guarantees, such as:

1. The outside glazing is wind and rain proof.
2. The outside glazing resists mechanical damage.
3. The dimension of the interspace guarantees a free circulation of the air (necessary openings on top and bottom and both sides, if necessary).
4. Construction should be planned so that alterations are possible, as the state of knowledge about the subject changes.

Various European countries shared their experiences/experiments with each other, especially through the CV Newsletter. Some of their findings are listed below.

* Inside ventilated protective glazing is preferred, subject to additional research
* PG should be easy to execute and as cheap as possible
* Aesthetically, solutions can be geometrical patterns, simplified lead lines, unreflecting panels. Interior light openings are ease to hide.

The need for long-term data was recognized, in order to obtain accurate knowledge about the effectiveness of the various PG systems. Measurements of PG needed to address temperature, relative humidity of the atmosphere and airstream speed in the interspace. It was suggested that measuring instruments be put together by experts which could be made available on an international level.

In England, for fear of spoiling the aesthetic appearance of architecture, isothermal glazing systems have not been used. Also due to results and recommendation from Roy Newton's Cathedral experiments. After some years, the use of isothermal glazing began to have its proponents, as it became apparent that non-vented exterior PG allowed condensation to collect, The cost of future maintenance of glass, frames and architecture seemed minimal compared to isothermal glazing.

According to S. Oidtmann in his recent doctoral thesis, there have been various experiments involving condensation and internal venting vs. external venting at York Minster, Sheffield and Canterbury since 1972. Varying conditions were observed: time of day of measurements, amount of time in sun/shade at time of measurements, differing spaces between the glazings, differing size of ventilation openings, diamond glazed leading and some full sheet PG, and heated/unheated churches. Due to the varying conditions, there did not seem to be conclusive results (see "Reported Results of Isothermal Glazing").

Keith Barley, a glass restorer at York Minster received a Churchill Fellowship in the mid-1980s to travel to the continent and investigate long existing systems. He returned to England and with cooperation of commercial manufacturers developed special manganese bronze frames so that isothermal glazing could more easily be accomplished. (CVMA Newsletter 45, July 1994, p. 26). Barley spoke of his findings and solutions in Philadelphia at the 1994 International Seminar on Stained Glass of the 19th and 20th Centuries; this seminar was co-sponsored by the Society of Architectural Historians and The Census of Stained Glass Windows in America.

A report in the 1993 Autumn/Winter periodical British Society of Master Glass Painters discusses a symposium conducted on conservation of stained glass in Britain. Keith Barley discussed methods of PG with ample illustrations; recognized the "enlightened attitude of the Church of Ireland in commissioning Dr. David Lawrence to make an inventory of windows...which contrasts with the attitude of the British Council for the Care of Churches who ignore these for some form of training in the care of historic buildings for those such as vicars charged with such care".

Dr. David Lawrence, advisor to the Diocese of Chichester, has drawn up guideline for architects working in that diocese. (Sarah Brown, by letter, 2/24/95). In subsequent communication with Dr. Lawrence, he sent his guidelines on window-protection which use information from English Heritage, the Council for the Care of Churches, the Corpus Vitrearum, and views of ecclesiastical architects and other stained glass conservators. The guidelines are summarized on the following page.

Diocese of Chichester, England protective glazing guidelines:

1. Double glazing is useful in the protection of medieval glass, provided that the ventilated system known as *isothermal glazing* is used.

2. Isothermal glazing is not normally used for modern glass, although is some cases it may be applicable.

3. There must be a good-sized aperture both at the top and bottom to allow air to flow.

4. Unventilated systems are positively harmful.

5. Stained glass within any double glazed system, vented or not becomes much hotter in sunlight that unprotected glass. Wide swings in temperature cause the stained glass panels to buckle.

6. Where double glazing encloses adjoining stonework, this is harmful to the stone.

7. Double glazing is not a substitute for restoration of stained glass.

8. The additional groove needed for PG often is cut into the mullions and jambs, which can weaken the structure.

9. Mullions will have to carry twice the weight for which they were designed; this may weaken the structure.

10. Sheet glass is not easy to remove to give access for inspection and maintenance.

11. Because double glazing is itself breakable, it cannot be seen as an effective guard.

12. Stainless steel wire guards, powder-coated wire guards or in special cases polycarbonate guards, provide the most effective protection against attack.

13. Double glazing has a bad aesthetic affect on the appearance of any building.

14. It is displeasing when joins in the sheet glass are determined only by the stock size of the sheet, without considering the architecture or the stained glass and the frames across the glass so as to be visible from the inside of the building.

EFFECT OF PROTECTIVE GLAZING ON CONDENSATION

Venting a PG system is complex but critical to successful protection without negative side effects. As just mentioned, the are numerous studies in Europe investigating the correct method of venting the interspace between the stained glass and the PG. There are four possibilities: to the exterior, to the interior, isothermal to the interior and no venting at all. The only absolute upon which all of the European studies agree, is that no venting is the worst possible alternative. All studies indicate that not venting the interspace results in increased levels of glass corrosion.

There are three primary reasons for venting: to allow any condensate to evaporate and leave the interspace; to equalize the pressure in the interspace with that of the local atmosphere; and to minimize damage to the lead came matrix due to metal fatigue induced by the increased expansion of the lead from the greater range of temperature experienced by unvented windows. The data gathered during this study in the United States confirms these facts.

The data becomes less conclusive as to the best method to vent the interspace. As stated earlier, it is important to determine the cause of the deterioration before a PG system can be designed to protect a window. Most of the studies done in Europe focus on medieval stained glass. Much of this glass derives its alkali from potash thereby making a glass very susceptible to corrosion from the weather and air borne pollutants. The primary concern of the scientists and craftsmen working to solve the *best method* in Europe is to keep condensation, precipitation and the exterior air from coming in contact with the fragile medieval glass, thereby inhibiting the process of corrosion. A secondary concern is the protection from impact damage, be it natural or man-made in origin. Two other factors appear to act as filters in their decision making process. First, the medieval glass is irreplaceable. It could be replicated to a degree, but the original glass is inherently valuable from both an artistic and historic point of view. Second, there is a limited number of windows left, therefore, a limited number to protect.

In America, the problem is quite different. Less than 1% of the stained glass in this country is as susceptible to corrosion from the elements as is the medieval glass. There are additional windows, possibly 5% of the total extant, that have unstable paint. As mentioned earlier, there are a small number of windows that should be covered for other technical reasons. The balance and overwhelming preponderance of the windows in the United States only need to be protected from the misguided actions of destructive people. The sheer volume of windows in this country dwarfs the number of medieval windows found in Europe. While many of our windows are important, only a small percentage of them approach the high inherent value found in the medieval panels.

The *best method* for protecting European windows may also be the *best method* for American windows, from a strictly scientific point of view. However, when other important components are considered, such as the possible alteration of historic facades and interiors, or the cost of the PG system, an alternative design may provide a better solution to the site specific needs of the stained glass windows to be protected. America can benefit greatly from the studies performed in Europe, but this should not translate into the blind acceptance of their chosen PG systems.

Based on the work completed in Europe, the consensus opinion for the best method of venting the interspace is an isothermal installation vented to the interior of the building. In this type of setting, the glazing material is set into the groove or rebate originally intended for the stained glass. The framing members of the window are then adjusted, or a new frame is built and installed on the interior of the building, to support the stained glass. The original setting type (i.e. individual panels on stout T bars or lead came to lead came meeting joints) and the perimeter shape of the window openings (i.e. rectangular, Roman arch, Gothic head with tracery, etc.) determine the complexity and extent to which the original frame must be altered to accommodate the isothermal setting.

The advantages of this system are twofold. First, the stained glass is completely separated from the exterior environment. Second, when properly installed, this system also minimizes the temperature differential that the stained glass experiences because the interspace is heated (or cooled) by the interior air. The interior volume of air always experiences a reduced temperature differential when compared to the air within the interspace of a window that is vented, but not isothermally. The level of protection from impact damage is the same as windows vented in other ways. It is determined by the glazing material installed on the exterior.

An isothermal installation should not be confused with simply venting the interspace to the interior, a correct installation is much more complex. The opening to allow for proper venting is quite substantial. A basic understanding of the forces at work is necessary to effect a proper design. The relative humidity (RH) of the interior air is often much lower than the RH of the exterior air. However, R.G. Newton in his studies in English cathedrals, illustrated that the RH is not always the best indicator of the likelihood of condensation forming on the windows. The low RH of the interior air is more a function of its higher temperature, and not an absolute measure of the amount of moisture it is carrying. The dew point (DP), the temperature at which a given volume of air will condense, is a much more reliable indicator. The DP of the interior air is often higher (thereby more likely to condense) than that of the exterior air. Newton's data indicates that for the coldest period in January, the RH of the exterior air was substantially higher (10% to 40%) than the RH of the interior air. However, for the corresponding times and RHs, the DP of the exterior air was lower (less likely to condense) than the interior air. This study was done in an unheated English cathedral. In heated American churches, the effect would be similar, but with a greater disparity between the DP of the interior and exterior air masses due to the increased capacity of the warmer air to hold moisture.

Where and how the glazing gets vented depends on the type of installation and the local environment. A key scientific premise to understand is that of relative humidity. Relative humidity (as opposed to moisture content) is not a finite measurement of the amount of moisture in a given volume of air. It is a ratio of the actual moisture content of a given volume of air divided by the maximum possible moisture content of an equal volume of air at a given equal temperature. The relative humidity of a given volume of air is inversely proportional to the temperature of the air. As the temperature of the air increases, its ability to hold more water increases.

If the interior air with the higher dew point is introduced into the interspace at a slow or restricted volume, it will cool. This can often lead to condensation between the stained glass and exterior glazing. A setting can only be considered isothermal when the velocity and volume of air moving through the interspace is sufficient to maintain a temperature close to that of the interior air. The spacing between the stained glass and the PG and the size of the vent openings at the top and bottom of the interspace determine the success or failure of the system. There are varying opinions as to the correct spacing and size of the vents. The thoughts on adequate spacing vary from 3 cm as posed by Alfred Fisher FMGP of Chapel Studio, Kings Langley, Great Britain in the CVM Newsletter of July, 1994; to 5 to 8 cm as posed by Dr. Jütte during a talk at St. Ann & the Holy Trinity in 1995.

There are similar disparities in regard to the size and relationship of the vent openings. One school of thought posits that the depth of the interspace is directly proportional to the width of the openings. Another presumes a more complicated relationship, and places greater dependence on the size of the openings than the width of the interspace. A convergence of these two opinions occurs when the position and effect of the openings is discussed. The openings should only occur at the top and bottom of the interspace. The ideal airflow through the interspace should be .5 m/sec, and a minimum of .4 m/sec., to maintain an isothermal situation. To get the full picture, one must also understand the insulating effect of boundary layers and the hydrodynamics of the air column moving through the interspace.

There a number of challenges to successfully achieving an isothermal installation. Very few installations in American churches easily convert to isothermal situations. Most often, the historic facade or interior window surround must be substantially altered, at great expense, to accommodate an isothermal setting of the PG. The cost factor can be three to five times more than an exterior-applied exterior-vented system. In the few situations where important, fragile, historic glass must be protected from any possible incidence of condensation and/or thermal expansion kept to an absolute minimum, the expense and possible architectural compromise of an isothermal system may be warranted. However, in the vast majority of U.S. installations, the isothermal approach would appear to be an overly protective solution. Further, the high cost of these systems can severely deplete the resources of the owner. The money would be better spent on other, more cost-effective conservation procedures.

It is clear from all of the studies that the interspace must be vented. If isothermal venting is overly protective, what is the more appropriate method for windows with stable glass and paint? J.M. Bettembourg of the Laboratoire de Recherche des Monuments Historiques (LRMH), Champs sur Marne, France presented a paper at the Ottawa Congress in September of 1994. The data of his study indicated virtually no difference between interior and exterior venting in the probability of condensation occurring on the interior surface of the stained glass in a PG installation. His data does indicate a higher probability of condensation occurring in the interspace when the system is vented to the interior. This supports the earlier findings of R.G. Newton in his study of English cathedrals. In a number of the papers written by the Europeans, even when an isothermal system is installed, it is often recommended to provide additional venting to the exterior to remove moisture from the interspace.

Where and how the glazing gets vented depends on the type of installation and the local climatic conditions. Exact specifications as to the amount of venting do not yet exist. It is clear that the best system is one that can be easily modified to allow for a greater or lesser airflow. Each site must be examined before determining the exact method of venting. There may be differences within the same building when moving from one elevation to another, or one micro-environment to another. Suggestions of how to vent are given below.

A northern temperate climate, as found in much of the United States and Europe, calls for venting of the interspace to the exterior of the building. As Bettemborg states, it may be necessary to increase the venting on the Southern elevation of the building to counteract the solar gain from sunlight. This is more important if the glass chemistry is such that it absorbs more heat from the sun, as many medieval glasses are wont to do. Newton found that excessive shade from a nearby tree, or projecting bit of architecture, can greatly alter the micro-climate of a window. Newton also found that if the bottom vents are made close to the material forming the window surround, the air drawn into the interspace is preheated by captured heat radiating from the mass of the building.

Exterior venting can be accomplished in several ways. If applied frames are used to support the protective glazing, holes can be drilled through the members of the frame to allow air movement. The holes must be at the top and bottom of the window, placed in such a way as to discourage the infiltration of rain water and insects. If plastic glazing is used, holes can be drilled through the plastic. Place them at the top and bottom of the lancet, and angle them up to prevent rain from coming in. If the exterior glazing is leaded, vent panels (stainless steel screens) can be glazed into the window during fabrication. If laminated glass is used, the corners can be cut off (or the top three inches of a Gothic Head) and a hooded vent screen made from glass, stainless steel screening and lead came, can be fitted to the system. The hood is a projecting piece of metal or glass that prevents water from entering the interspace.

A southern temperate climate, such as the hot, humid sections of the Southeastern United States may call for different venting methods. Here, venting to the interior should be considered if the building is constantly air-conditioned. This may demand a minor alteration of the frame, or setting the stained glass on blocks and allowing the air to pass beneath the bottom panel and over the top panel.

As stated earlier, the venting needs of particular windows may vary greatly. The amount of venting required is dependent on the window's micro-environment. Whenever possible, install one window as a test installation. Monitor all installations throughout the year and inspect for evidence of condensation, such as moisture trails on the interior surface of the stained glass or PG. Presently, there are no set specifications to determine the exact amount of venting. One must use common sense, and be willing to constantly review the results of past work. In general, larger vents are better than small ones. If there was no evidence of condensation before the PG was installed, it is unlikely that it will occur after an externally vented PG system is installed. As Bettemborg states, the likelihood of condensation lessens as the thermal resistance of the stained glass window is increased.

It is better to not apply protective glazing, than to apply it improperly. The most common result of an improper installation is condensation. Churches are notorious for neglecting maintenance, particularly on high windows; paints and sealants nearly always fail before they are renewed causing leaks into (often) unvented PG. Moisture is trapped between the glazing and condenses, on the stained glass, PG, framing members and surround of the window. Moisture promotes corrosion of the glass. Condensate accelerates glass corrosion all the more due to its chemical purity. The condensate corrodes metals that may be part of the window system. As steel or iron rust, they expand in size. This expansion can put substantial pressure on the stained glass window, often resulting in deflection of the panels or breakage of glass. If the oxides produced dissolve in additional condensate, they can migrate, resulting in staining of the glass or the window surround.

Water can leach organic acids from certain types of wood. The organic acids oxidize the lead cames, turning them to a fine white powder. Water encourages wood rot. The rot usually begins at the sill of the window, or within sections of the tracery where water can collect. As the wood rots, it loses its rigidity. This allows the window to compress and settle into the damaged wood frame. This can result in deflection or glass breakage.

Humid and wet conditions within the interspace can encourage the growth of micro-organisms. The micro-organisms trap minute amounts of water close to the surface of the stained glass, where it does the most damage. Micro-organisms may excrete it organic acids than can attack the lead cames. As the micro-organisms respire in the interspace, carbon dioxide is released. This mixes with the water vapor and forms an organic acid which attacks the lead came.

Less prevalent in the United States, but critical to a complete understanding of the problem, are the effects of an improperly vented system on fragile paint. In depth studies of paint failure in this country do not exist, however, once again we can take advantage of studies from Europe. At Orvieto cathedral in Orvieto, Italy medieval glass with fragile paint was studied. The glass had PG installed approximately 100 years ago. Potash as well as soda lime glasses were found in the windows. The causes of paint loss as found at the Orvieto in a study by M. Marabelli, P. Santopadre & M. Verità are: separation due to a difference in the coefficients of expansion of the substrate glass and the ground glass of the paint; absence of elemental inter-diffusion (the paint never quite fused with the glass substrate) between the substrate and the glass paint (more common in the soda lime glass due to higher softening temperature); in some of the potash glass, the corrosion had occurred in the glass beneath the paint; possible presence of stress generating organic films deposited for restoration purposes.

The writers concluded that the external protective glazing has a protective effect, as it attenuates thermohygrometric variations, and separates the glass from the weather. The separation of paint is due to the chemical composition of the paint and the glass substrate, resulting in differing coefficients of expansion and melting temperatures, and that the primary bond between the two is a physical one. The increased temperature differential caused by an improperly vented window will exacerbate the separation of paint from the substrate. Condensation that may form will accelerate the corrosion that may occur beneath the paint, thereby hastening its loss. If organic

films have been employed to consolidate fragile paint, the extreme temperature differential can cause the films to expand and contract at different rates, possibly lifting the paint the films were designed to protect, resulting in permanent loss.

A late arrival to the field of PG systems is the process of placing the stained glass panel within a triple-glaze,d insulated unit. A sandwich comprising clear glass, the stained glass and a second layer of clear glass is fabricated. The edges are sealed and the interspace is partially evacuated or filled with an inert gas such as argon. The early prototypes of this system quickly failed due to edge sealant failure. The sealant on the edge was not compatible with the waterproofing compound used on the stained glass panel. Once the integrity of the seal is breached, the panel quickly fogs up due to condensation. The use of space-age technology employing materials that are more compatible and purported to last longer, has resulted in an increased longevity for panels fabricated with this system.

The benefits of this system are the increased energy efficiency of the panels and the separation of the stained glass from collecting dirt and smoke deposits from the environment. Laminated or tempered glass can be used to provide maximum protection from impact. The panels are protected from impact on both sides. However, the drawbacks are numerous. While longer lasting than the early prototypes, the insulated unit is destined to fail well before the stained glass panel will. This will necessitate expensive maintenance of the system, entailing the removal and remaking of failed units. The added weight of the second piece of plate glass may accelerate the deterioration of the supporting frames. The system cannot be installed into stone tracery or surrounds without a major alteration of the stonework, or a resizing of the original stained glass panels resulting in a permanent loss of historic glass. The spacing available between the leaded glass and the plate glass is too small to provide space for adequate support barring on large panels. If round bars are used, they will not tie into the supporting frame and there fore will provide little or no support.

No studies have been done to measure the surface temperature of the lead came matrix trapped within this PG system as the panel is heated and cooled during a typical daily cycle. In the absence of such testing proving otherwise, this system must be treated as a non-vented system. The one consistent fact from all of the studies is that this is the worst condition to put stained glass in. The reflective surface of the applied clear glass will interfere with the appreciation of the stained glass from both the exterior and the interior. Encasing the stained glass in a triple-glazed, insulated system may be desirable for small windows used in a residential or a commercial space. This PG system, due to the many drawbacks described above, does not appear appropriate for ecclesiastical installations.

All PG systems add to the solar gain absorbed by the stained glass throughout the day. If the interspace is improperly vented, the temperature differential can be quite dramatic. Lead has a high coefficient of thermal expansion and a low modulus of elasticity. For a given change in temperature, the lead came will expand along its length. When it cools, it does not return to its original size and shape like steel does. The pressure generated by this expansion is enormous. The pressure causes the window to deflect from its original design plane. An

unvented interspace can be subject to extreme temperatures as solar radiation is absorbed through the day. The absorbed heat is transferred directly to the window augmenting the deleterious effects of the expansion and contraction cycle. If plastic glazing is used, adequate provisions must be made for the high degree of expansion they experience (up to 1/8" per lineal foot). Deep glazing grooves and flexible caulk must be used in these applications. If not allowed for, the expansion of the plastic will tear the existing framing apart.

EFFECT OF PROTECTIVE GLAZING ON HEAT BUILD-UP

Unvented protective glazing has a "greenhouse effect" on the air space between the stained glass and the secondary storm glazing. Solar radiation is absorbed by the protective glazing, stained glass and frame and converted into heat. In America, this effect only occurs on unshaded east, west and south elevations. Naturally, the south elevation gets the longest exposure to direct sunlight and therefore normally registers the highest temperatures. The west elevation typically registers higher temperatures than the east since the ambient air temperature on a sunny day normally increases throughout the day. Wind speed and direction can have a significant effect on reducing glass and air space temperatures. However, some of the greatest discrepancies between air space temperature and outdoor temperature occur during the winter months when the sun is low in the sky (low angle of incidence) and shines more directly on southern windows. Finally, the color and type of glass also effect temperatures significantly, light opalescent windows absorb less heat than traditionally darker "medieval-style" windows.

During the Protective Glazing Study, Inspired Partnerships measured the surface temperature of 100 windows under various environmental conditions but nearly always under direct exposure to sunlight. The surface temperatures ranged from a low of 72° to a high of 118°. Moreover, dataloggers were installed in the air space of two unvented south-facing opalescent windows of medium color density at St. John's Church near Chicago. These dataloggers monitored daily air space temperature and humidity every twenty minutes from May 1995 to May 1996. While the outdoor temperature varied between a low of -15°F and a high of 120°F, and the indoor temperature generally ranged between 55°F and 75°F, the air space temperatures varied between a low of 4°F and a high of 165°F! Perhaps more important than the temperature peaks and valleys recorded is the exaggerated temperature swings in unvented PG installations. On November 19, 1996, a sunny day, the outdoor temperature fluctuated 14°F and indoor only 13°F, but the air space fluctuated 88°F!

Although few people question the effect of heat build-up, some people question whether it is relevant to the deterioration of stained glass. The Europeans have paid less attention to heat build-up but rather concentrated on moisture and pollution issues which they have correctly identified as causing the most serious deterioration of <u>medieval</u> glass. However, Inspired Partnerships' field survey revealed that some American windows are having problems which seem related to heat build-up; southern windows are generally in worse condition than other facades as typical of roof and wall materials with southern exposure. Moreover, southern windows covered with unvented PG appeared to be deforming (sagging and buckling) more than windows that were not covered.

It is interesting to note that few imported windows, plated windows, windows made with ¼" or larger came, and higher quality windows made by the most reputable American studios show few signs of heat-related deterioration. However, temporary or "catalog" windows, particularly those produced around World War I or fabricated with narrow 1/8" came, were seriously effected by heat build-up. In other words, the increased heat caused by unvented PG does not seem to be a significant factor for well designed and fabricated stained glass. It does seem to accelerate the deformation of lesser quality windows. Unfortunately, this process occurs over years, sometimes decades, and is difficult to demonstrate under real weathering conditions (as opposed to accelerated laboratory tests).

All building materials have a "coefficient of thermal expansion" (COTE) which represents their measurable change in size depending on their exposure to various temperatures. The higher the COTE, the more the material moves from thermal changes. Some building materials, particularly metals, have a high COTE and must be designed to accommodate considerable expansion-contraction movement. Lead and zinc came for instance, have a COTE of .0000183 and .0000174 respectively, compared to .0000067 for steel, .0000047 for glass, and .0000021 for wood, all typical materials found in stained glass windows. Therefore, the expansion-contraction of lead and zinc came from thermal changes is approximately three times that of steel, four times glass, and seven times wood!

The process that results in deformation of stained glass panels is a consequence of the creep characteristics of lead came. The controlling parameters of this process include: 1) panel size, 2) shape and size of the glass pieces in the panel, 3) lead came size, profile and strength, and 4) placement and attachment of reinforcement. This makes the actual calculation of deformation and extremely formidable task. However, it is possible to make statements about the long term deformation of stained glass based on an equation for the creep characteristics of lead as a function of load and temperature.

An equation for the creep of lead has been developed based on some theoretical considerations and a set of creep measurements for "commercial lead." More accurate determination of the constants could be made with creep measurements on modern came which was not uncovered, but this data is sufficient to demonstrate the nature of the conclusions which may be made. The equation for lead creep is shown on the following page.

The first term in this equation is the elastic response of lead to stress. The magnitude of this term is very small and is included only for completeness. The second term in the equation is the plastic response of lead to stress. This plastic response is usually called the first stage of creep. Its magnitude is much larger than the elastic response, but is small compared to the long term effects of second stage creep (the third term in the equation). Second stage creep is the actual flow of the metal. It continues indefinitely, coming to an end only when the lead fractures. This is the reason viscosity appears in the third term. The units of viscosity are unconventional (usual units would be ft-lb/sec-sec) but are convenient in this application.

$$\mathrm{CREEP}(\sigma,t) := \left[\frac{\sigma}{E} + \left(\frac{\sigma}{Pl}\right)\cdot e^{\frac{T-70}{Tc}}\cdot\left(1 - e^{-\frac{t}{tc}}\right) + \left(\frac{\sigma\cdot t}{\mu}\right)\cdot\left(\frac{\sigma}{E}\right)^{2}\cdot e^{\frac{T-70}{Tc}}\right]\cdot 100$$

t := time(hours)

σ := stress$\left(\frac{lb}{in^2}\right)$

E := modulus_of_elasticity$\left(\frac{lb}{in^2}\right)$

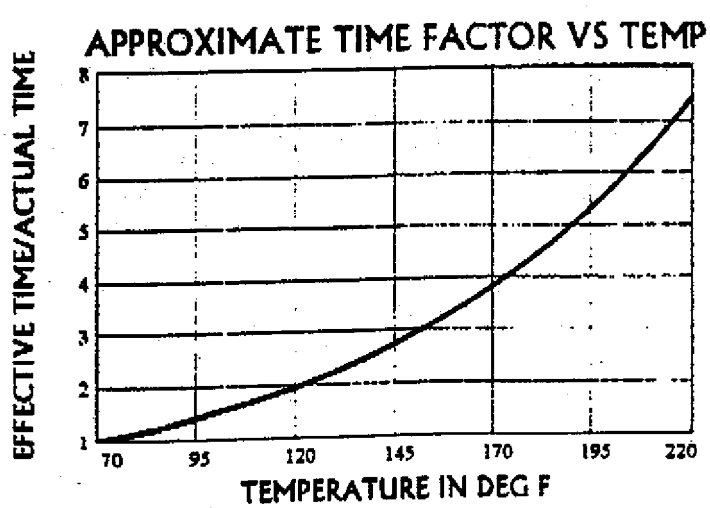
Pl := modulus_of_plasticity$\left(\frac{lb}{in^2}\right)$

Tc := characteristic_temperature_effect(degrees_F)

tc := characteristic_time_effect(hours)

μ := viscosity$\left(\frac{lb\cdot hours}{in^2}\right)$

The value of E (modulus of elasticity) was taken from the literature, but the four other constants were determined by data reported in: Mechanics of Engineering, H.F. Moore and M.B. Moore, McGraw-Hill, 1953. If creep data on lead came exists in later literature, the constants could be revised. The purpose of this work is simply to make inferences with respect to deformation of stained glass panels as affected by temperature. The relationship of time and temperature on lead creep is shown in the following chart.



Appendix 1 presents a MathCad Plus 6 program which compares calculated creep as a function of stress and time with measured values, all at 70°F. The agreement is quite good. Appendix 2 presents a second MathCad program which computes on year creep at three temperatures and compares the calculations to measured data. Again, the agreement is quite satisfactory.

Computation of the deformation of a stained glass panel as a function of its geometry and reinforcement is currently beyond the state of the art. However, from the equation and experimental data, it is clear that the flow temperature term in the equation is dominate at long times. This makes is possible to evaluate the effect of temperature on stained glass deformation as a factor of time. If a leaded glass panel is going to deform, it will deform more rapidly when exposed to higher temperatures. The preceding graph presents this relationship. For instance, deformation will proceed twice as fast at 118°F (the highest surface temperature measured during the survey) than at 70°F. It is presumed that the surface temperature of the came facing an unvented air space is higher yet with temperatures potentially reaching 150°F. In this case, deformation could occur up to three times faster than uncovered windows during the period it is exposed to direct sunlight.

It appears that leaded glass in unvented installations is somewhat self-relieving. That is, panels deform from the initial heat build-up, but the deformation creates gaps between the came, putty and glass that allow the window to vent itself. This is particularly true of new, or recently releaded windows installed with weathertight, unvented PG. These supertight new or restored windows produced the highest temperatures. Therefore, deformation is accelerated on the front end of the window's life which is the least desirable.

The service life of a stained glass window, at least one that is particularly susceptible to deformation due to inferior design, fabrication, or materials, could be reduced by years due to unvented PG. Unfortunately, there are far too many variables between stained glass windows and ever-changing weather to accurately estimate the accelerated deformation as a direct result of heat build-up from unvented (or under-vented) PG. Further studies are required into creep characteristics, exposure, and the thermal effect of sunlight on uncovered stained glass.

Three general approaches are employed to minimize thermal expansion-contraction: 1) reduce the thermal exposure; 2) select materials with lower coefficients of expansion, or 3) design expansion or control joints to allow for movement and prevent binding or buckling. Alternative materials and control joints are not viable options for stained glass, but removing, or at least venting PG to reduce thermal exposure and temperature swings is always an option.

One of the two St. John windows were vented during the study to determine the impact on heat build-up. The Lexan® panel measured 33" x 76" (2,508 square inches). In this panel, three ¼" holes were drilled at the bottom and top totaling .294 square inches (.0001% of the total area); later this was doubled to .589 square inches (.0002%). The holes were kept small to minimize the aesthetic impact, however, the overall results on relieving heat build-up were disappointing. Nevertheless, even this minimal amount of venting lowered peak temperatures 10°F below the unvented PG. It also appeared to reduce humidity and condensation problems.

CONSERVATION DESIGN ISSUES

When designing the installation details of a protective glazing system, the following factors must be considered: the existing condition of the window and its surround, the effect on the aesthetics of the window and the building, the appropriate materials to use, the venting of the interspace and the ease with which the system can be maintained. The owner should be aware of the present condition of the stained glass of the windows to be covered. Carefully examine the leaded glass, supporting frame, and window surround for signs of deterioration. Special care should be given to areas of unstable paint or severely deflected lead matrices. These conditions should be monitored after installation of PG to ensure that the deterioration is not accelerated. PG cannot fix existing problems, it merely covers them up.

There are aesthetic as well as structural elements to this aspect of the design. The individual merits of the different glazing materials are described above. Use framing materials that complement the existing materials of the building. Avoid, where possible, large sheets of plastic (that will deflect) or glass (that will reflect), both distracting to the architectural aesthetic of the building. Do not use dissimilar metals that may encourage galvanic corrosion. Electrically isolate such metals when their pairing cannot be avoided. This will inhibit galvanic corrosion. When securing new framing materials to the existing building fabric, consider and allow for the coefficients of expansion of the different materials to avoid damage as the elements experience the heating/cooling cycle. If polycarbonate is used a glazing material, use a deep rebate frame to allow for its high rate of expansion. Silicone is the only caulk that will adhere well to polycarbonate. Silicones that release acetic or other organic acids while curing must not be used in the presence of leaded windows.

While wood can be used to fabricate frames to hold protective glazing, metal is usually more appropriate. A much larger section must be used with wood, which may obscure part of the stained glass window. Aluminum is the current metal of choice. In strong salt conditions (such as near the ocean) special coatings or alloys should be specified so that the aluminum does not corrode. All fasteners should be nonferrous. The protective glazing framework should be attached to the surround of the window and be securely anchored. The PG frame work should only be attached to the existing frame of the stained glass it is to protect after careful investigation has determined that the original frame can support the additional weight. If plastic is used as a glazing material it must be placed into an adequate frame. It should never be screwed onto the existing wood frame.

A common mistake on many PG projects is the application of the secondary glazing "piggy-backed" onto the existing single-glazed ventilator sections. If operable vents are desired, a custom double-glazed ventilator must be fabricated to accommodate the stained glass and the protective glazing. While aluminum, double-glazed ventilators are readily available, they are more appropriate for new installations for which the large size of the sections can be accounted for during the design process. For historic restoration projects, bronze or steel ventilators are more appropriate. The narrow profiles available in these metals will accommodate the historic glass without altering the original panel size thereby obviating the loss of historic glass.

Wire screens are often a good option to the protective glazing materials covered in Section III, and are gaining favor, particularly in Europe. Wire screens can be inexpensive and quite effective in the prevention of vandalism and impact damage to stained glass windows. They allow for the periodic rinsing of the windows from the exterior with a hose. Screens also provide a degree of security from unauthorized entry to the building. The parameters to consider when designing this type of system are: the material of the screen; the size of the wire and the mesh; and the method of attachment to the building.

The least expensive material is galvanized wire but it should be avoided for churches due to the high maintenance required to preventing rusting. Copper or bronze may also be used to fabricate screens but are more expensive than galvanized. Copper, if left unpainted, can also result in staining of the building particularly light-colored stones. The longest-lasting material needing the least maintenance is stainless steel which is also the most expensive. Whichever material is used, it should be painted, blackened or stained to a dark color. The screens will then minimally interfere with the appreciation of the stained glass and building from the exterior.

A possible negative result of installing wire screens to protect stained glass windows is the shadow of the wire through the screen. This type of protection may not be suitable for very transparent, lightly tinted stained glass windows. It can be quite effective for heavily painted antique glass, textured glass or opalescent glass windows. Dr. Jütte, Department for the Care of Ancient Buildings, The Netherlands and others in Europe, have studied the problem. To minimize the shadow effect, the consensus opinion recommends the use of the smallest gauge wire that can maintain rigidity over the given span. The size of the mesh, or spacing between the wires, should be quite small, one quarter of an inch or less. The screen is deemed acceptable if it allows the transmission of 95% of the available light through the stained glass.

The screens should be placed relatively close to the stained glass. Individual screens should be made for each panel in the lancets and the tracery. The smaller panels allow for a lighter gauge material to be used and facilitate required repairs and maintenance. Existing ventilators can be used by creating a cage into which the window can open, or by fixing individual screens to each ventilator. Care should be given to the choice of fasteners. In general, they should be nonferrous and compatible with the other metals and materials found in the system.

All stained glass and their window frames need regular maintenance to ensure a long serviceable life. The PG system should be designed to allow for periodic maintenance work to the frames. The applied frames used to support the PG should cover as little of the original frame as possible. It is a misconception that covering all of the wood of a frame with PG will obviate the need for constant maintenance of the wood. The enemies of wood and its painted surface are ultra-violet radiation, heat, and the movement of water through the wood. These factors are rarely negated by the application of PG, and are often made more destructive when the PG is incorrectly applied.

Most windows in the United States do not have to be protected from anything other than vandalism. The most stable, albeit most expensive protective glazing system is an isothermal one. This system ensures that the temperature on both sides of the historic glass are similar. An excellent combination of cost-effectiveness, protection against vandals and allowance for the proper micro-environment can be provided by the use of laminated glass vented externally. If absolute protection from vandals is needed, laminated glass is the material of choice in all but the most extreme cases. Mausoleums for instance, where security is often a much greater issue than aesthetics, may warrant polycarbonates. As in all endeavors, the careful consideration of all existing conditions and needs will result in the most appropriate application.